

# STATE OF THE ART AND FUTURE DIRECTIONS FOR THE ATOMIC HYDROGEN MASER

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## ABSTRACT

The present status of technology development for atomic hydrogen masers (H-masers) is reviewed. The limitations to frequency stability and accuracy are discussed with emphasis on the problems associated with cavity resonator instability and the lack of reproducibility and stability of the storage volume wall coating frequency shift. New types of coatings developed in the Soviet Union and better, cavity resonator materials, are expected to make possible frequency at the  $10^{-16}$  level at  $10^4$  sec. Better control of systematic effects should extend the long-term stability to levels better than  $10^{-15}$  for intervals beyond one day. Present use of H-masers as flywheel oscillators in timekeeping systems is discussed as is the outlook for the future cryogenic and room temperature H-masers as flywheel oscillators to operate very high resolution frequency discriminators based on the newly evolving technology of trapped and cooled ions and atoms.

## 1. INTRODUCTION

It is now 30 years since the invention of the atomic hydrogen maser<sup>1</sup> by D. Kleppner and N. F. Ramsey and its technology has matured in several different directions aimed toward a variety of uses and technical requirements.

The principal applications of the H-maser derive from its excellent short term stability. Since the mid 1960s H-masers have been used in widely separated radio telescopes for very long baseline interferometry (VLBI) to control local oscillators and provide timing for data recording. Signals recorded from radio sources are later brought together for correlation to obtain extremely precise angular information of their brightness distributions.

H-masers are now almost exclusively used for tracking spacecraft. Range information is obtained by measuring the time delay of time-coded signals. Range-rate information is obtained by measuring the Doppler shifts of transponded signals. Angle information is derived using the VLBI technique, where simultaneous measurement of spacecraft signals are made at two or more widely separated tracking stations.

Since the H-maser can provide frequency stability at better than 1 part in  $10^{14}$  over intervals of several days, during the past decade it has proven itself as a flywheel oscillator in timekeeping applications. With the advent of the United States' Global Positioning System and the Soviet Union's GLONASS system, a highly precise local time scale can be kept by operating H-maser oscillators as clocks and applying occasional time and frequency corrections from observations of GPS and GLONASS space clocks using the "common-view" technique.

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The Soviet Union operates more than a hundred of H-masers as working time and frequency standards in timing centers that serve their vast territories; these clocks are kept synchronized and syntonized by a variety of techniques.

Since this paper is intended to discuss the state of the art it is appropriate to define the nature of the art. The plan of this paper is first to look at the art of obtaining the very best frequency stability over intervals up to about  $10^5$  seconds, how to cope with the systematic effects that impair maser long term stability, followed by a brief description of the technologies now in use for operating H-masers and, lastly, to offer a view of the future for H-Masers.

## 2. THE HYDROGEN MASER OSCILLATOR

The H-Maser is an oscillator powered by quantum transitions between two energy levels in the hyperfine structure of atomic hydrogen. At room temperature the population of hydrogen atoms is nearly evenly distributed among four magnetic hyperfine levels designated by  $F=1$ ,  $m_F=1, 0, -1$  and  $F=0, m_F=0$ . These energy levels depend on the relative orientations of the magnetic dipoles associated with the proton and the electron when the atom is in a magnetic field.

In the upper energy level, designated by  $F=1$ , the angular momenta of the proton and electron are aligned and added; their magnetic dipoles are also aligned. In this state the total angular momentum can orient itself with a magnetic field in three different directions and the  $F=1$  energy level splits into three components. The  $F=0$  energy level results from the alignment of protons and electrons that cancel their total angular momentum and their magnetic dipoles oppose each other. The energy levels of atomic hydrogen are shown in the upper part of Figure 1.

Figure 1 also shows a schematic diagram of the H-Maser oscillator. Molecular hydrogen at a pressure of about 0.1 Torr is dissociated by an r.f. plasma discharge and collimated into a beam. Atoms in two of the upper magnetic hyperfine energy levels ( $F=1$ ,  $m_F=1$ , and 0) are selected by passing through a highly inhomogeneous magnetic field generated by a multipole permanent magnet which causes them to move toward the weak field near the axis of the magnet. These atoms are focussed into a storage bulb located in a resonant cavity tuned at the atomic hyperfine frequency. The storage volume confines the atoms to a region where the oscillating magnetic field is in the same phase. Generally, a  $TE_{011}$ -mode resonator is used, as shown in Figure 1.

As the atoms proceed from the multipole magnet into the cavity bulb region, the magnetic field they encounter field changes from about 9KGauss radially in the magnet to about one Gauss along the axis of the beam. In this "drift region," the atoms remain in the  $F=1$ ,  $m_F=1$ , and 0 state and will be kept in these states as they proceed along the drift region if the magnetic field they encounter is reduced to the level of the field in the resonator without sudden interruption or change of direction.

The all-important feature of the H-Maser is the surface coating that enables its operation as an oscillator with a narrow resonance linewidth, or high line Q. This is achieved by storing the atoms without appreciable loss of phase coherence from collisions with the wall surfaces or among each other. At room temperature the atoms travel at about 2.5 km/sec, and in a typical two liter storage

vessel, whose collimator provides a one second storage time, a typical atom undergoes  $10^5$  collisions before leaving the vessel

The frequency of the  $F=1, m_F=0$  to  $F=0, m_F=0$  transition that powers the oscillator depends on the static magnetic field as  $\Delta f_m = 2751 B^2$  (where  $B$  is in Gauss). To avoid frequency shifts from changes of magnetic field, H-Masers are operated at low magnetic fields, usually of about 1 milligauss. To maintain these low fields and to provide a spatially uniform field, with variation at the microgauss level throughout the bulb, magnetic shields are placed about the resonator to attenuate the outside ambient field, and a solenoid is placed within the innermost shield to provide a uniform and controllable field.

The line Q of the H-maser is defined as  $Q_l = \pi f_0 / \gamma_2$ , where  $f_0$  is the oscillation frequency and  $\gamma_2$  is the total rate of loss of phase of the atoms' oscillating dipole moment with respect to the phase of the signal in the resonator. The parameter  $\gamma_2$  includes loss of phase coherence by escape from the bulb and from recombination to form molecules, also loss of phase coherence from wall collisions, magnetic inhomogeneities and interatomic collisions. Maser oscillation is sustained when the energy released by the incoming atoms resulting from stimulated emission by the microwave fields in the resonator exceeds the energy lost by the resonator. The energy lost includes the signal delivered to the receiver.

The state of the art of microwave receiving systems for H-masers is an important topic that will require a separate discussion outside the context of this paper.

## 2.1 FUNDAMENTAL LIMITS OF FREQUENCY STABILITY

The fundamental stability limit for the H-Maser is the same as for other oscillators.<sup>2</sup> Following Kleppner and Ramsey in reference 1, it is given as

$$\sigma_y(\tau) = \frac{1}{Q_l} \sqrt{\frac{kT}{2P\tau}} \quad (1)$$

where  $\sigma_y(\tau)$  is the Allan standard deviation of the fundamental limits to frequency stability over time intervals,  $\tau$ .  $Q_l$  is the quality factor of the oscillating system operating at a power level,  $P$ ,  $k$  is Boltzmann's constant, and  $T$  is the absolute temperature.

From this expression we see that to obtain the best stability we want high oscillation power and high values of line Q. However these are incompatible situations since high power implies high levels of atomic flux and, consequently, high levels of interatomic collisions.

The power levels normally generated in H-Maser oscillators are low, rarely more than -90 dBm, and the signal-to-noise ratio of the equipment that receives the maser signal has a very significant effect on the maser's short-term stability ( $\tau < 100$  sec.). The effect of the added noise on the Allan standard deviations is<sup>3</sup>

$$\sigma_y(\tau) = \frac{1}{2\pi f_0} \left[ \frac{FkTB}{P} \frac{1+\beta}{\beta} \right]^{1/2} \quad (2)$$

Here  $F$  and  $B$  are the receiving system noise figure and bandwidth,  $P$  as before, is the oscillator power and  $\beta$  is the cavity resonator coupling factor that determines the power delivered to the receiver.

Thermal noise,  $kT$ , appears in equation 1 as the noise power within the linewidth of the oscillator and in equation 2 as the effective noise,  $FkT$ , within the bandwidth  $B$  of the receiver system. In both cases there are advantages to operating a maser at low temperatures.

The maser oscillator's power variation with beam flux is determined by the design of the maser and can be characterized by a quantity  $q$ , which depends on the following maser parameter<sup>4</sup>

$$q = \frac{h}{16\pi^2 \mu_0^2} \sigma(T) v(T) \frac{\gamma_t}{\gamma_d} \frac{V_c}{\eta V_b} \frac{1}{Q_c} \frac{I_{\text{tot}}}{I}. \quad (3)$$

Here  $h$  is Planck's constant,  $\mu_0$  is the Bohr magneton,  $\sigma(T)$  is the hydrogen atom's spin-exchange collisional cross section,  $v(T)$  is the average relative velocity of atoms,  $\gamma_d$  is the rate of loss of phase coherence from the loss of atoms,  $\gamma_d$  is the rate of loss of phase coherence from all causes, including loss of atoms but excluding the effect of interatomic collisions, and  $V_c/V_b$  is the ratio to cavity to storage bulb volume,  $\eta$  is the "filling factor", the ratio of the average axial component of the r.f. magnetic field squared to the square of the r.f. magnetic field averaged throughout the cavity. The quantity  $I_{\text{total}}$  refers to the rate at which the total number of atoms enter the bulb and  $I$  is the rate at which atoms in the desired  $F=1, m_F=0$  state enter the bulb.

Plots of the normalized output power to beam flux are shown in Figure 2, from reference 4, for various values of  $q$ . Note that it is possible to stop oscillation by having too many atoms, that smaller values of  $q$  provide higher power for a given flux, and that for  $q > 0.172$ , the maser will not oscillate.

### 3. SYSTEMATIC EFFECTS

Figure 3 shows how the Allan standard deviation representing the frequency stability of the H-Maser follows the behavior predicted by the combination of equations 1 and 2 up to a point where systematic effects intrude on the maser's behavior, in this case for intervals beyond  $10^4$  seconds. The most serious systematic effect is the "pulling" of the oscillation frequency by the mistuning of the cavity resonator. The frequency of oscillation of the aggregate of atoms stored in the maser storage volume includes systematic frequency shifts induced by interatomic collisions and the loss of phase coherence is proportional to these collisional shifts.<sup>5</sup> Another systematic frequency shift that is related to the inter-atomic collision rate is the magnetic inhomogeneity (MI) frequency shift that occurs when the following conditions pertain. 1) When there is an asymmetry in the population of the  $F=0, m_F = +1$  and  $-1$  magnetic hyperfine sub-levels of the atoms entering the bulb and 2) when there exists a magnetic field inhomogeneity over the volume of the bulb and 3) when there exists an asymmetry in the distribution of r.f. magnetic fields over the volume of the bulb. Since the inhomogeneity and symmetry requirements, 2 and 3 above, are difficult to fulfill, the MI shift is present in nearly all H-Masers with magnetic state selectors that focus atoms in both the  $F=1, m_F=1$  and  $m_F=0$  states.

The least well understood systematic frequency shift in the atomic hydrogen maser is the effect of collisions with the surfaces of the storage volume wall, known as the "wall shift". Many questions still remain unresolved about the nature of the collision processes. These include the collision interaction energy, its effect on the advance or retardation of the phase of oscillating dipole moment of the atom and the amount of its phase decorrelation. Surface smoothness, which determines the collision rate, depends on how the coating is applied. The variability of the wall shift from maser to maser is the chief obstacle to achieving frequency accuracy.

Little work on surfaces has been done in Western countries since FEP-120 Teflon was adopted in the mid-1960's. The most significant advance since then has been made in the Soviet Union by Demidov et al.,<sup>6</sup> who report substantial improvement in the reduction of the wall shift by using a new fluoroplastic that they designate as F-10. The eight-to-ten times smaller wallshift of F-10 that, in part, results from its highly superior surface smoothness, allows a correspondingly smaller variability in the wall shift.

The question of long-term frequency stability of the wall shift, as yet, is not resolved. Considerable insight about the present status of this question will be gained by reading the report on the session on wall coatings that appears in these proceedings.

For a more thorough discussion on systematic frequency shifts please see the paper on the physics of such shifts by E. M. Mattison<sup>7</sup> in these proceedings.

### 3.1 CAVITY RESONATOR MISTUNING

The shift in the output frequency  $\Delta f_c$  from cavity mistuning is given by

$$\Delta f_c = \Delta f_R Q_c/Q_l. \quad (3)$$

where  $\Delta f_R$  is the resonator's frequency offset from the atomic oscillation frequency. We note that the penalty for reducing  $q$  by raising  $Q_c$  is to make the maser more subject to cavity pulling. Typically,  $Q_c$  is about  $5 \times 10^4$  and  $Q_l$  is about  $2.5 \times 10^9$ , so that  $\Delta f_c = \Delta f_R \times 2 \times 10^{-5}$ . For fractional frequency stability at a level of 1 part in  $10^{15}$  we require  $\Delta f_R$  to be kept within 0.07 Hz. For frequency stability at this level, without active frequency control by a servo system, we require good control of the resonator's temperature, and a cavity material with a very low coefficient of thermal expansion, along with excellent mechanical stability. In terms of cavity dimensions for a typical TE<sub>011</sub>-mode resonator, whose axial tuning rate is about 10 MHz/cm, the axial dimension must be kept constant to less than  $7 \times 10^{-9}$  cm. This is about the diameter of a hydrogen atom! If we assume that we can control temperature at a level of  $2 \times 10^{-5}$  °C we require a linear temperature coefficient smaller than  $5 \times 10^{-8}$  °C. Materials such as Zerodur,<sup>8</sup> Cer-Vit,<sup>9</sup> and ULE<sup>10</sup> are available that have comparable values of thermal coefficients<sup>11</sup> but this is not the whole story. There is also the temperature coefficient of the dielectric constant of the storage bulb, which also causes a frequency shift. The resonator's frequency is affected by everything with which it can interact. This includes the storage bulb within the resonator, all the electronics coupled to the resonator, including the resonator tuning system, and the circuits that couple power to the receiving system.

There is no all-purpose, optimum technique for coping with the resonator frequency drift. When predictability of the frequency drift is important, H-masers designed with the best available materials and techniques for passive stability have been satisfactory. The ageing of Cer-Vit and the other glass-ceramic materials is very predictable, once the initial settling-in of the resonator end covers to their cylinder has taken place, a process that requires some three to six months.<sup>12</sup> To control the effect of cavity pulling there are limits to how far we can increase the value of  $Q_l$ , because of the resulting decrease in the available output power and the loss of short-term stability. It is clear that some form control, or of monitoring, of the resonance frequency of the cavity is desirable for long term frequency stability of masers. Three types of active servo techniques have been used.

1. By line Q modulation and searching for a tuning condition, such that  $\Delta f_c$  is zero.<sup>13,14</sup>
2. By cavity resonance frequency modulation and adjusting the resonator, such that the output signal amplitude is optimized.<sup>15</sup>
3. By introducing signals into the cavity at frequencies away from the oscillation frequency and near the inflection points of the resonator's frequency response.<sup>16</sup> The relative levels of the signals that are sent through the cavity are compared and kept fixed by adjusting the center frequency of the cavity.

Line Q modulation requires a frequency reference with stability comparable to that of the maser being tuned during the period of modulation. Ideally, another maser is employed for this purpose. There are usually sidebands at the modulation frequency in the output signal. This method produces a signal whose frequency depends on the atomic resonance including wall collision shifts. The H-H collisional shifts are cancelled by an offset in the resonator frequency because they are proportional to the collisional line broadening.

Cavity resonance frequency modulation makes possible a H-maser with good stand-alone qualities of frequency stability. As in system No. 1, the modulation signal will be present in the output signal unless some form of compensation is employed. This method adjusts the resonator to the atomic resonance frequency including the wall shift and the H-H collisional shift, which can vary with beam flux.

The last technique mentioned above has been used successfully in masers having very small cavity resonator-storage bulb combinations that have been designed using dielectric loading methods or the lumped capacitor loading.<sup>17</sup> Since using this type of resonator often requires external electronic gain to raise the resonator's quality factor and, under these conditions, the resonator frequency is further subject to the phase stability of the Q enhancing amplifier.

Injecting the probing signals requires scrupulous avoidance of any additional noise or signal at the maser's oscillating frequency to avoid pulling the frequency of the maser oscillation. This method maintains the resonator at some pre-assigned frequency. Beam flux variations will cause changes in output frequency depending on how the resonator frequency is related to the atomic oscillation frequency.

### 3.2 MAGNETIC FREQUENCY SHIFTS

Systematic frequency shifts from changes in ambient magnetic field result from two different physical processes, 1) a change in the internal magnetic field in the storage volume causing changes in  $\Delta f_m = 2751 B_{int}^2$  and 2) a change in the MI frequency shift,  $\delta(\Delta f_{MI})$ , resulting from time variations in the spatial uniformity of  $B_{int}$ , time variations in the hydrogen density in the bulb, and time variation in the state distribution of atoms entering the bulb.

The first processes results from having finite magnetic shielding capability. Well annealed arrays of high quality shielding material can achieve shielding factors,  $S = \delta B_{ext}/\delta B_{int}$  as high as  $10^5$ . If we assume a value for  $S$  of  $5 \times 10^4$ , and operate with  $B_{int}$  at a level of  $5 \times 10^{-4}$  Gauss we have that

$$\frac{\delta(\Delta f_m)}{f} = \frac{5502}{f_0} B_{int} \frac{\delta B_{ext}}{S} = 4 \times 10^{-14} B_{ext}. \quad (4)$$

Given that variation in  $B_{ext}$  can be confined to 0.015 Gauss (or a few percent of the earth's ambient field) we can expect systematic fractional frequency variations of about  $6 \times 10^{-16}$ . It is clear that more layers of magnetic shielding can be added, or that a magnetic field compensation servo system can be used, if more severe conditions are encountered.

The second physical process causing magnetically induced frequency shifts is far less straightforward than the process described above. It depends on the inequality of the population difference in the  $F=1$ ,  $m_F=+1$  and  $-1$  states entering the bulb, the asymmetry of the RF magnetic fields in the storage volume, and the DC magnetic gradient in the storage volume. Under conditions where these populations are not equal and with the almost inevitable lack of RF symmetry and field uniformity in today's equipment, the output frequency of the maser will vary with beam flux. This causes problems with the flux tuning process described in equation (3), where the frequency shift owing to spin-exchange collisions is assumed to be strictly proportional to the atomic density. (Even in cases where there is no  $\Delta f_{MI}$ , the cavity resonance is still offset in frequency by the amount required to compensate for the spin exchange collision frequency shift, which is proportional to the atomic density.) The stability of the magnetic inhomogeneity shift,  $\Delta f_{MI}$ , will depend on the constancy of the state distribution of atoms and on the interatomic collision rate.

Removal of the MI shift can be done by providing a beam of atoms exclusively in the desired  $F=1$ ,  $m_F=0$  state or by equalizing the population of atoms in the  $F=1$   $m_F=+1$  and  $-1$  states. The state distribution of atoms entering the storage volume can be equalized by changing the direction of the axial magnetic field in an alternating manner in the drift region downstream from the state selecting magnet shown in Figure 1. When this field is in the same direction as the field in the bulb, the beam proceeds in the normal states. When the drift region field is inverted under proper conditions, the  $F=1$  states can be inverted. The  $m_F = +1$  population then appears in the  $m_F = -1$  state. By alternating the direction of the drift region field the average population of the  $m_F = +1$  and  $-1$  can be equalized. This technique is used in the Soviet Ch1-75 H-maser.

A more effective, but more complicated method to provide a beam of atoms nearly exclusively in the  $F=1$ ,  $m_F = 0$  state is discussed in section 4.2 of this paper. Using this system the entire population of atoms will generate signal power with one half the rate of interatomic collisions and provide an improvement in the line Q.

### 3.3 WALL COLLISION FREQUENCY SHIFTS

The most fundamental problem today with the H-maser is the lack of reproducibility and time stability of the wall coating frequency shift. The wall shift is the principal source of maser frequency inaccuracy. Since the wallshift is proportional to the wall collision rate multiplied by the phase shift per collision, ideal coatings should be as smooth as possible and of a material capable of producing the smallest possible phase shift per collision. The original masers built in 1960-1962 used coatings of dimethyl-dichloro-silane (dri-film). In about 1962 Teflon was found to be far superior to dri-film and Teflon has been used since that time.

Coatings of PTFE (poly-tetra-fluoro-ethylene), a long-chain fluorocarbon with a high melting point were originally used. These coatings are difficult to apply and are rarely used today. When a PTFE coating is slowly cooled after melting it crystallizes and has a wallshift with a small temperature coefficient. On the other hand, when the coating is rapidly cooled after melting, it has a larger wallshift and a larger dependence with temperature. It has zero wallshift at about 82 degrees C.<sup>18</sup> PTFE has rarely been used since 1965.

FEP fluorinated-ethylene-propylene, a branched fluorocarbon with lower melting point than PTFE is far easier to apply than PTFE, and to date, has been the most widely used coating in masers made in the US and Europe.

A far superior coating called "Fluoroplastic F-10" has been developed in the Soviet Union specifically for H-masers.<sup>19</sup> It melts at a lower temperature than PTFE, flows evenly over the surface and has 8 to 10 times lower wallshift than PTFE and FEP Teflon. This new material should substantially improve the accuracy capability of H-masers.

## 4. A SUMMARY OF TECHNOLOGIES USED IN TODAY'S HYDROGEN MASERS

### 4.1 HYDROGEN MASER RESONATORS

The most often used resonator operates in the  $TE_{011}$  mode. Without appreciable dielectric loading by the bulb, the resonator's typical dimensions are of a cylinder 28 cm dia. x 28 cm long. This allows use of storage bulbs of 2 to 3 liter capacity. Smaller resonators have been made using dielectric loading. These resonators suffer large variations of resonance frequency with temperature owing to the thermal coefficients of dielectric constant of the loading material and require more strenuous autotuning or thermal control than unloaded resonators.

Resonators with smaller dimensions, using lumped capacitance loading to reduce dimensions, are used in passive H-masers and regenerated-Q H-masers. This resonator is in use in the Soviet Ch1-76 H-maser, in some masers built by the Sigma-Tau Standards Corporation (where the idea originated) and in the small regenerated-Q spaceborne masers developed at the Hughes Corporation.

Stabilization of the resonator can be done either by passive means, using materials of high mechanical stability and with very low coefficients of thermal expansion, or by active means, discussed in 3.1. Rough tuning of the resonators is usually done with a mechanical device that in some way slightly alters the internal configuration of the resonators r.f fields. Fine tuning (over a range of a few tens of Kilohertz) is usually done with a varactor coupled to the resonator either directly, as part of a coupling loop or probe, or via a transmission line.

## 4.2 ATOMIC HYDROGEN STATE SELECTION

The H-maser uses traditional molecular beams techniques with multipole magnets to concentrate atoms in the desired quantum states into a beam aimed into the collimator of the storage volume. Four-pole magnets and six-pole magnets are commonly used. Small diameter four-pole magnets are more efficient in their use of hydrogen than six-pole magnets. Six-pole magnets have focussing properties analogous to optical lenses and can be used to focus a specific range of velocities from the modified Maxwell distribution of velocities of atoms emerging from the source to form a real "image" of the source aperture. While the narrowness of the velocity distribution can be less efficient of hydrogen use, these magnets are useful for operating a state selector that provides a beam of atoms wholly in the desired  $F=1, m_F = 0$  state.

A method to provide a beam of atoms nearly exclusively in the  $F=1, m_F = 0$  state is shown in Figure 4.20. Here, the first magnet, in the usual way, focusses a beam into a second magnet of twice the length that, in turn, refocusses the beam as an image of the source aperture at "stop 2" in the figure. An Adiabatic Fast Passage (AFP) radiofrequency transition is made in the space between the magnets to invert the population. Only atoms in the  $F=1, m_F = 0$  states continue through the magnet and on to the bulb.

## 4.3 MAGNETIC SHIELDS AND FIELD CONTROL

The multilayer magnetic shields in use today appear to be adequate for controlling both the level of magnetic fields and their gradients in the storage volume of H-masers. Systematic frequency shifts resulting from the magnetic conditions in "normal" environments, with variations of a few milliGauss, appear, for the present, to be well enough controlled in most masers. However, as progress continues in the control of other systematic effects other than of magnetic origin, better shielding will be required. A typical example of the shielding factor is  $S = \Delta H_{ext} / \Delta H_{int} = 10^5$  for  $\pm 0.5$  Gauss external variations in  $\Delta H_{ext}$ . A wider range of cancellation of external magnetic field variations can be achieved with active servo methods by sensing the external field and applying a compensating field.

The control of internal magnetic gradients by multi-section coils so far has proved adequate. Simple degaussing techniques using currents at powerline frequencies to remove remanent fields in the magnetic shields have also been adequate.

Uses of superconducting materials for magnetic shields operated at low temperatures and for conductive coatings of cavity resonators are being considered. The combination of these functions is a very tempting prospect particularly if room temperature, or even low temperature, superconductors become available. Superconducting shields are eminently useful and appropriate for H-masers operating at very low temperatures.

#### **4.4 HYDROGEN SUPPLY, PURIFICATION AND CONTROL**

Two types of hydrogen supply systems are presently in use, high pressure gas bottle systems and low pressure sources operating by heating some form of metallic hydride such as Li Al H<sub>4</sub> to release hydrogen. These systems require control of the flow and purification of H<sub>2</sub> before it proceeds to the dissociator. Both regulation of flow and purification are achieved by passing the H<sub>2</sub> through heated metal tubes, plugs, or diaphragms depending on the pressure of the supply.

Gas bottles can be easily vented and refilled to comply with airline transport regulations and are a simple, reliable, low-tech devices requiring only a pressure gauge to give a measure of the gas available.

Metallic hydrides are light in weight, small in volume, do not require a pressure vessel and are thus ideal for spacecraft operation. A metal hydride system is used in the Soviet Ch1-75 H-maser system along with a self-heated thin walled nickel tube for flow control and purification of H<sub>2</sub>.

#### **4.5 DISSOCIATORS TO PRODUCE ATOMIC HYDROGEN**

In H-masers the dissociation of molecular hydrogen is done by r.f. plasma excitation. The ideal choice of surfaces for the dissociator is one that will not adsorb hydrogen on its surface so as to allow recombination with incoming colliding atoms. Surfaces of glasses that are free of metal oxides and of pure fused silica appear to be the best.

Excitation of the plasma is done by exposure to r.f. fields, either by electrodes that produce predominantly electric fields, or by a coil that produces induced displacement-current fields. The latter method causes less erosion of the glass since it is essentially an electrodeless discharge, but requires a means for starting the discharge such as a spark coil or a minuscule amount of radioactive " $\alpha$ " particle emitter as a "keep alive" to provide ionization to initiate the plasma discharge. The plasma in the glassware presents a variable impedance to the excitation circuit that depends on the hydrogen pressure. This variability can cause difficulties in matching the r.f. power to the plasma. Single transistor oscillator circuits are commonly used, where the glass or quartz cell containing the plasma is included in the resonant circuit. In these circuits the resonant frequency adjusts itself to changes in

the reactance of the cell when the plasma is started and as the hydrogen pressure is varied. These devices are simple and cheap, but often temperamental and difficult to stabilize.

External r.f. power sources with a wide band match to the plasma cell are less power efficient, but more predictable. Another advantage is that external power sources can be operated at known and fixed frequencies well away from frequencies whose harmonics, if leaked into the maser receiver, could cause problems. The capability of monitoring of incident and reflected power to the plasma is another useful feature.

## 4.6 VACUUM SYSTEMS AND HYDROGEN SCAVENGING

The use of the ion pump was probably the most significant departure in the evolution of the H-maser from the experimental laboratory environment to the marketplace. Ion pumps are still widely used and some have been specifically designed for pumping hydrogen. For pumping hydrogen the situation is different from the normal ion pump process where a hail of sputtered cathode material particles bury adsorbed gas molecules on surfaces in the pump. Since hydrogen is readily assimilated by the titanium cathodes, in principle there is no need for ionic bombardment and sputtering. However this process is substantially assisted by the scrubbing of the cathodes by the impacting of hydrogen ions. Other species of ions, being heavier, cause the usual pumping by sputtering and burial of gases.

Early ion pumps used in H-masers had cathodes in the form of plates that were attached at their corners and were subject to bending inward and short circuiting to the anodes as the engorged hydrogen warped the plates. This problem was easily cured by adding extra supports to the cathodes. The principal mode of failure of ion pumps in H-masers is related to local stress caused by hydrogen in titanium cathodes.<sup>21</sup> The stress causes spalling and flaking with momentary arcing and eventual short circuiting. Methods for improving the lifetime of operation include annealing of the plates at high temperatures under high vacuum and the selection of high purity titanium.

The use of sorption technology to scavenge hydrogen in H-masers began in 1973 in an effort to reduce the weight of a maser for a space experiment to measure the gravitational redshift,<sup>22</sup> Because sorption cartridges will pump hydrogen almost exclusively at room temperatures the addition of a small ion pump was found to be necessary to pump other gases. This ion pump, which is usually operated at a lower than normal voltage to minimize hydrogen ion bombardment of its cathode, serves to dissociate hydrocarbon gases allowing the freed hydrogen to be pumped by sorption. With sufficient voltage it will operate at an acceptable speed to cope with argon, nitrogen, oxygen etc.

Sorption systems, with an ion pump backup are used in the Soviet Ch1-75 and Ch1-76 H-masers,<sup>23</sup> in the regenerated Q<sub>+</sub> space masers developed at Hughes, and in the Smithsonian Astrophysical Observatory's VLG-12 masers operating with the AFP single state selector. Because of the sensitivity of sorption systems to contamination, use of all-metal seals is recommended in place of elastomer seals.

Sorption cartridges that have reached their pumping capacity can repeatedly be reactivated by applying power to their internal heaters and pumping away the evolved hydrogen. The activation temperatures are high, near 700° C, and provision must be made to prevent damage to other nearby systems during activation. Because this process does not require disassembly of the maser, there is little likelihood of contamination of the maser's storage volume wall coating during activation.

Precautions are taken in maser vacuum systems to avoid materials with ferromagnetic properties for structures within the innermost magnetic shield. Titanium, copper, aluminium and carefully selected silicon bronze are some of the materials used inside the magnetic shields. Outside of the magnetically sensitive regions, vacuum manifolds are usually made of stainless steel, often with copper Con-Flat seals. Indium seals have been successfully used in conjunction with components made of softer metals such as copper and aluminium.

## 5. A LOOK TOWARD THE FUTURE OF ATOMIC HYDROGEN MASERS

Atomic hydrogen masers are principally used as flywheel oscillators with outstandingly good short term frequency stability that reaches levels deep in the  $10^{-16}$  domain over time intervals between 1 and  $10^5$  seconds. Today, on average, the accuracy of frequency reproduction of masers is about  $5 \times 10^{-14}$  and it is clear that H-masers do not compete with cesium beam devices as a primary standards.

The advent of trapped atoms and ions cooled by laser interactions has led to possibilities for frequency discriminators capable of extremely high resolution. These devices will require oscillators having very high frequency stability and capable of producing signals with frequency spectral densities commensurate with, or narrower than, the linewidths of the new discriminators. It is likely that H-masers will be used to supply these signals in future primary frequency standards.

H-masers will continue to be used in applications where the best possible stability is required for intervals between 1 second and  $10^5$  seconds. The limitations imposed by systematic effects that become evident beyond  $10^5$  seconds are now better understood and, as better wall coatings surfaces such as of the Soviet 'Fluoroplastic F-10' material are used, the fundamental limitations to frequency stability and will be improved. Frequency stability at the level of one part in  $10^{16}$  should be attainable in the near future with the best presently available coatings. Further improvement beyond this level should result with even better wall coatings.

The most recent breakthrough in H-maser technology was made in 1986 by operating H-masers at temperatures near 0.5 K using storage volume surfaces of superfluid helium-4. Researchers at the Massachusetts Institute of Technology,<sup>24</sup> the University of British Columbia,<sup>25</sup> and at Harvard University<sup>26</sup> all succeeded in achieving sustained oscillation. These research groups all used very different experimental configurations of cryogenic H-masers.

Cryogenic apparatus for operating apparatus at temperatures near 0.5 K is no longer considered exotic. The use of continuously operated  $^3\text{He}$  recirculating refrigerators or of dilution refrigerators for operating H-masers is definitely within today's state of the art.

The limits to the stability of cryogenic H-masers still have to be measured. New theoretical quantum mechanical analyses of H-H collisions have been made that predict limitations due to previously unknown processes related only to the storage time of atoms in the maser.<sup>27</sup> Research is now in progress to measure the properties of low temperature hydrogen collisional interactions with hydrogen and helium to test the new theory.

Figure 5 shows the layout of the cryogenic H-maser mentioned in reference 25. Its frequency stability, projected from all known effects of its design is given in Figure 6. This plot includes limitations owing to receiver noise resonator instability, and the instability of the predicted new frequency shifts. A plot of the spectral density of the maser's spectral density of phase fluctuations is shown in Figure 7. This figure shows the white phase noise corresponding to the  $\tau^{-1}$  behavior of the stability plot shown in Figure 6.6.

## 6. SOME OBSERVATIONS ON PRESENT AND FUTURE H-MASERS

In this paper the writer has tried to shed some light on the state of the art of atomic hydrogen masers. Since it is only recently that we, in the United States, have had the opportunity to appreciate maser developments made in the Soviet Union, this brief survey is bound to be incomplete.

In comparison with the technological development of other types of frequency standards in the West there has been only a few people involved in H-maser development. In the West it is only recently that development is headed toward designs suitable for small scale production. On the other hand the Soviets have placed far more reliance on H masers as working standards than we have in the West. They have already produced many hundreds of H-masers, and are now offering both active and passive H-masers for sale.

The market for H-masers in the West has, so far, been limited. However applications for masers are growing in number as signals of high frequency stability rather than of high accuracy become more in demand in view of the significant improvements in time transfer offered by two -way time transfer with communication satellites, the Global Positioning System and the Soviet Union's GLONASS system.

The development of H-masers still has a long way to go to reach its full potential as a highly stable oscillator. Improvements in the long term stability of room temperature H-masers are foreseen by use of new wall coatings and better control of systematic effects. Cryogenic H-masers wth stability at the  $10^{-17}$  to  $10^{-18}$  level and outstandingly high spectral purity will likely serve as oscillators for operating standards based on future high resolution frequency discriminators using trapped and cooled ions and atoms. The unique quality of the H-maser as an active oscillator, with unparalleled frequency stability for intervals up to  $10^5$  seconds and excellent long-term predictability of its fre-

quency variation, has led to its successful use as a “flywheel clock” at the U.S. Naval Observatory and at other timing centers.

The outstanding long-term (year-to-year) frequency stability of the ensemble of Soviet H-masers reported by N. B. Kosheyevsky and S. B. Pushkin<sup>28</sup> and the predictability of the behavior of H-masers discussed by Uljanov, Demidov, Mattison, Vessot, Allan and Winkler,<sup>29</sup> have proven the validity of new strategies for timekeeping. Precise time transfer by operating with common view GPS and Glonass signals makes possible the precise comparison of H-maser frequency over the long-term and enables these devices to serve as excellent flywheel standards.

Further advances in time transfer using active H-masers in orbiting spacecraft to permit time transfer at the few picosecond level will be required to keep up with the performance of future primary standards based on frequency discriminators operating with trapped ion and cooled atoms and ions.

It is clear that the technology of the atomic hydrogen masers, which is now only 30 years old, has still to reach its full maturity.

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## REFERENCES

- 1 D. Kleppner, H. M. Goldenberg , “Theory of the atomic hydrogen maser,” *Phys. Rev.* vol. 126, 603-615, 1962.
- 2 W A. Edson “Noise in oscillators,” *Proc. IRE* , vol. 48, pp. 1454-1456, 1960.
- 3 R. Vessot, L. Mueller, and J. Vanier , “The specification of oscillator characteristics from measurements made in the frequency domain,” *Proc IEEE*, vol. 54, no 2, pp. 199-207, 1966.
- 4 D. Kleppner, H. C. Berg, S.B. Crampton, N.F. Ramsey, R.F.C. Vessot, H.E. Peters and J. Vanier, “Hydrogen-maser principles and techniques,” *Phys. Rev.* ,Vol 138, Number 4A, 1964
- 5 S . B. Crampton, “Spin exchange shifts in the hydrogen maser,” *Phys. Rev.* vol. 158, pp. 57-61, 1967.
- 6 N.A. Demidov, E.M. Yezhov, V.A. Fodorov, A.A. Ul’janov. “The search for new materials in the hydrogen generator,” *UDK* 621.317.7.6.089.69.
- 7 E.M. Mattison, “Physics of systematic frequency variations in hydrogen masers,” in these proceedings.
- 8 Zerodur is a trademark of Schott Glasswork, Inc.
- 9 Cer-Vit is a trademark of Owens-Illinois, Inc.

- 10 ULE is a trademark of Corning, Inc.
- 11 E.M. Mattison and R.F.C. Vessot, "Time and temperature stability of silver-coated ceramics for hydrogen maser resonant cavities," *Proc. 20th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, p. 313, 1988.
- 12 R.F.C. Vessot and E.M. Mattison, W. J. Klepczynski, I.F. Silvera, H.P. Godfried and R.L. Walsworth, "Results of two years of hydrogen maser clock operation at the U.S. Naval Observatory and ongoing research at Harvard-Smithsonian Center for Astrophysics", *Proc. 17th Annual Precise Time and Time Interval P.T.T.I Meeting*, Washington, D.C., Dec. 3-5, 1985; pp. 413-431.
- 13 J. Vanier and R.F.C. Vessot, "Cavity Tuning and Pressure Dependence of Frequency in the Hydrogen Maser," *Applied Physics Letters* Vol. 4, Number 7, 1964
- 14 J. Vanier, H.E. Peters and R.F.C. Vessot, "Exchange Collisions, Wall Interactions, and Resetability of the Hydrogen Maser," *IEEE Trans. on Instrumentation and Measurement*, Vol. IM-13, Number 4, pp. 185-188, December, 1964
- 15 H.E. Peters, "Design and Performance of New Hydrogen Masers Using Cavity , Frequency Switching Servos," Sigma Tau Standards Corporation, *Proc. of the 39th Annual Symposium on Frequency Control*, pp. 420-425, 1984
- 16 C. Audoin, "Fast Cavity Auto-tuning systems for hydrogen masers," *Revue Phys. Appl.* Vol 16, pp. 125-130, 1981.
- 17 H.E. Peters, "Atomic Standards with reduced size and weight," U.S. Patent Number 4123777, October 31, 1978.
- 18 R.F.C. Vessot and M.W. Levine, "Studies of Hydrogen Maser Wall Shift for High Molecular Weight Polytetraflouroethylene," *Proc. 24<sup>th</sup> Annual Symposium on Frequency Control*, 27-29 , U.S. Army Electronics Command Ft. Monmouth, NJ. pp. 270-276, 1970.
- 19 N.A. Demidov, E.M. Yezhov, V.A. Feodorov and A.A. Ul'janov, ref. UDK621.317.7.6.089.69]
- 20 E. M. Mattison, R.F.C. Vessot and W. Shen, "Single-state selection system for hydrogen masers," *IEEE Transactions on Ultrasonics, Ferroelectronics, and Frequency Control*. UFFC-34, No. 6, pp. 622-628, Nov. 1987.
- 21 N.A. Demidov, E.M. Ezhov and A.A. Ul'janov, "On the duration of hydrogen evacuation by magnetic-discharge pumps," *Instruments and Experimental Techniques*, Vol. 21, pp. 739-740, 1978.
- 22 R.F.C. Vessot, M.W. Levine, E.M. Mattison, T.E. Hoffman, E. A. Imbier, M. Tetu, G. Nystrom, J. J. Kelt, Jr., H.F. Trucks, and J.L. Vaniman, "Spaceborne hydrogen maser design," *Proc. of the Eighth Ann. Precise Time and Time Interval Applications and Planning Meeting*, Washington, D.C., December; pp. 277-354.
- 23 N. A. Demidov and A. A. Uljanov, "Design and industrial production of frequency standards" in these proceedings.
- 24 H.F. Hess, G.P. Kochanski, J. M. Doyle, T. J. Gretyak, and D. Kleppner, "Spin-polarized hydrogen maser," *Phys. Rev. A*. Vol. 34, 1602 (1986)

- 25 M.D. Hurliman, W.N. Hardy, A.J. Berlinsky, and R.W. Cline, "Recirculating cryogenic hydrogen maser," *Phys. Rev. A*, Vol 34, 1605 (1986).
- 26 R.L. Walsworth, I. F. Silvera, H.P. Godfried, C.C. Agosta, R.F.C Vessot and E.M. Mattison, "Hydrogen maser at temperatures below 1K," *Phys. Rev. A*, Vol. 34, 2550 (1986).
- 27 J.M.V.A. Koelmann, S..B. Crampton, H.T.R. Stoof, O.J. Luiten and B.J. Verhaar, "Spin exchange frequency shifts in cryogenic and room-temperature hydrogen masers," *Phys Rev. A*, Vol. 38, Number 7, pp. 3535-3547 (1988)
- 28 N. B. Koshalyaevsky and S. B. Pushkin "USSR National time unit keeping over long intervals using an ensemble of H-masers" in these proceedings.
- 29 A. A. Uljanov, N. A. Demidov, E. M. Mattison, R. F. C. Vessot, D. W. Allan and G. M. R. Winkler "A comparison of Soviet and U. S. hydrogen masers" in these proceedings.

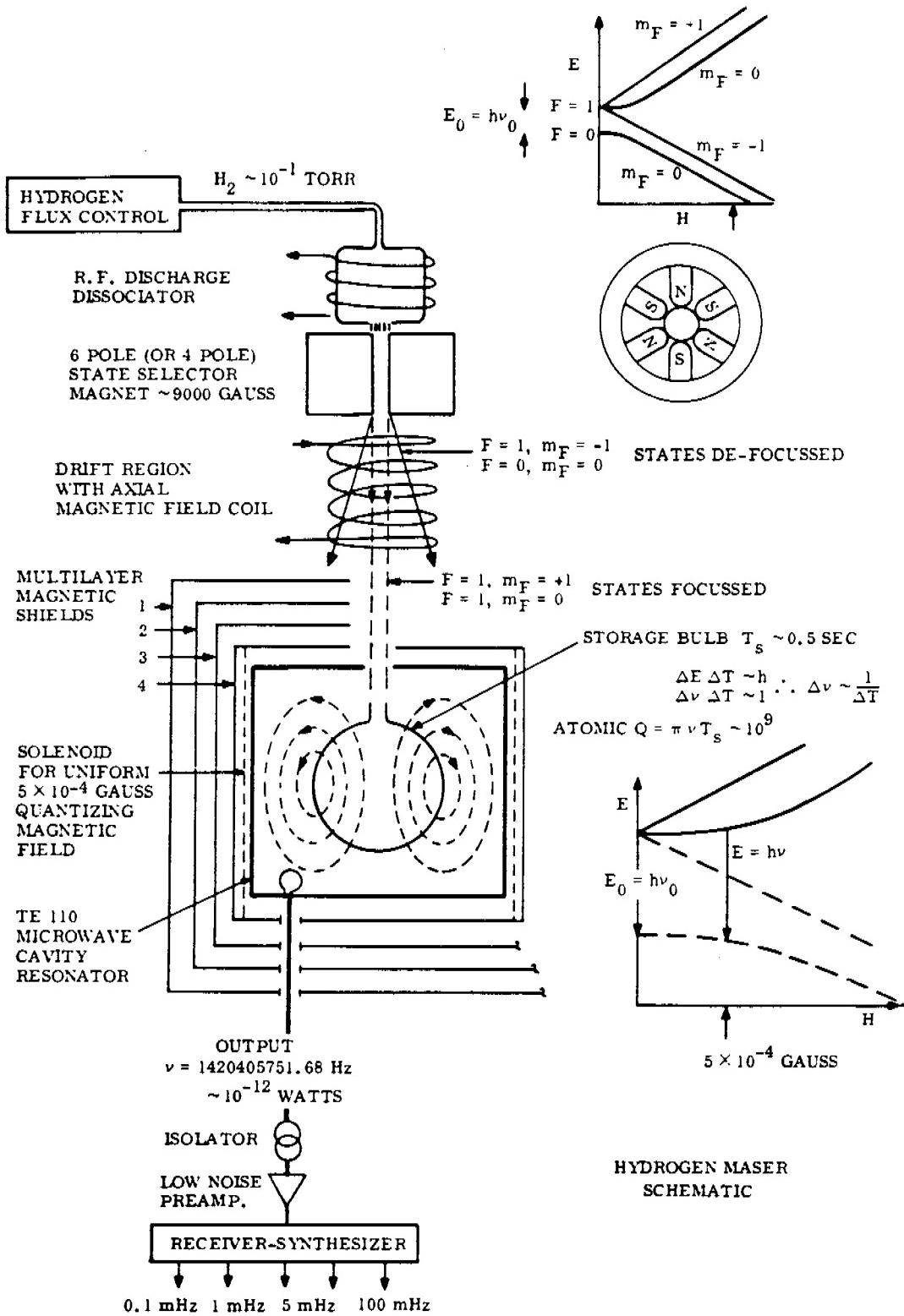


Figure 1. Energy levels of atomic hydrogen and a schematic diagram of the H-maser.

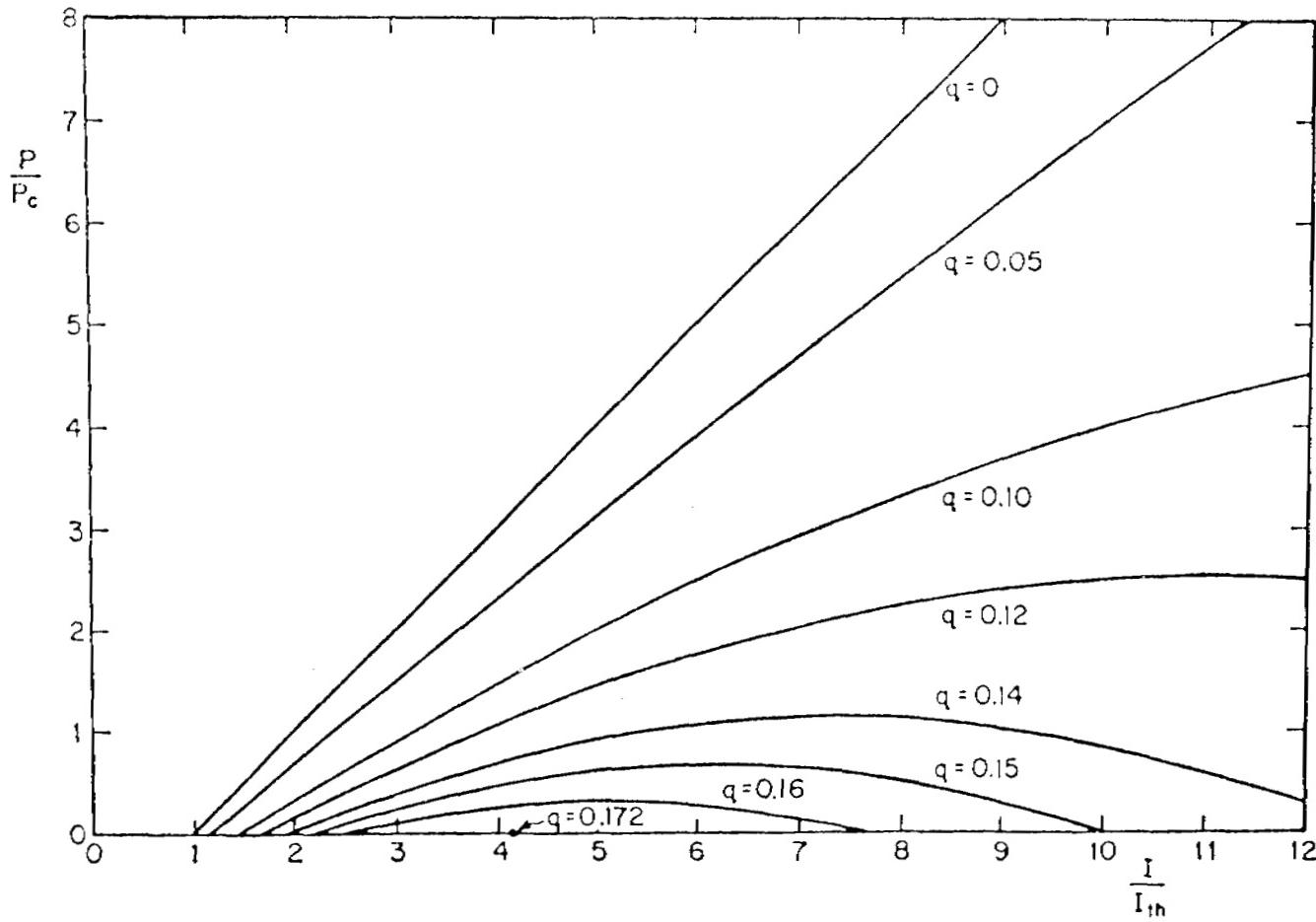


Figure 2. Oscillator power versus flux of atomic hydrogen

From "Hydrogen Maser Principles and Techniques"  
D. Kleppner, H.C. Berg, J.B. Crampton,  
N.F. Ramsey, R.F.C. Vessot, H.E. Peters  
and J. Vanier, Phys. Rev. 138, May, 1965.

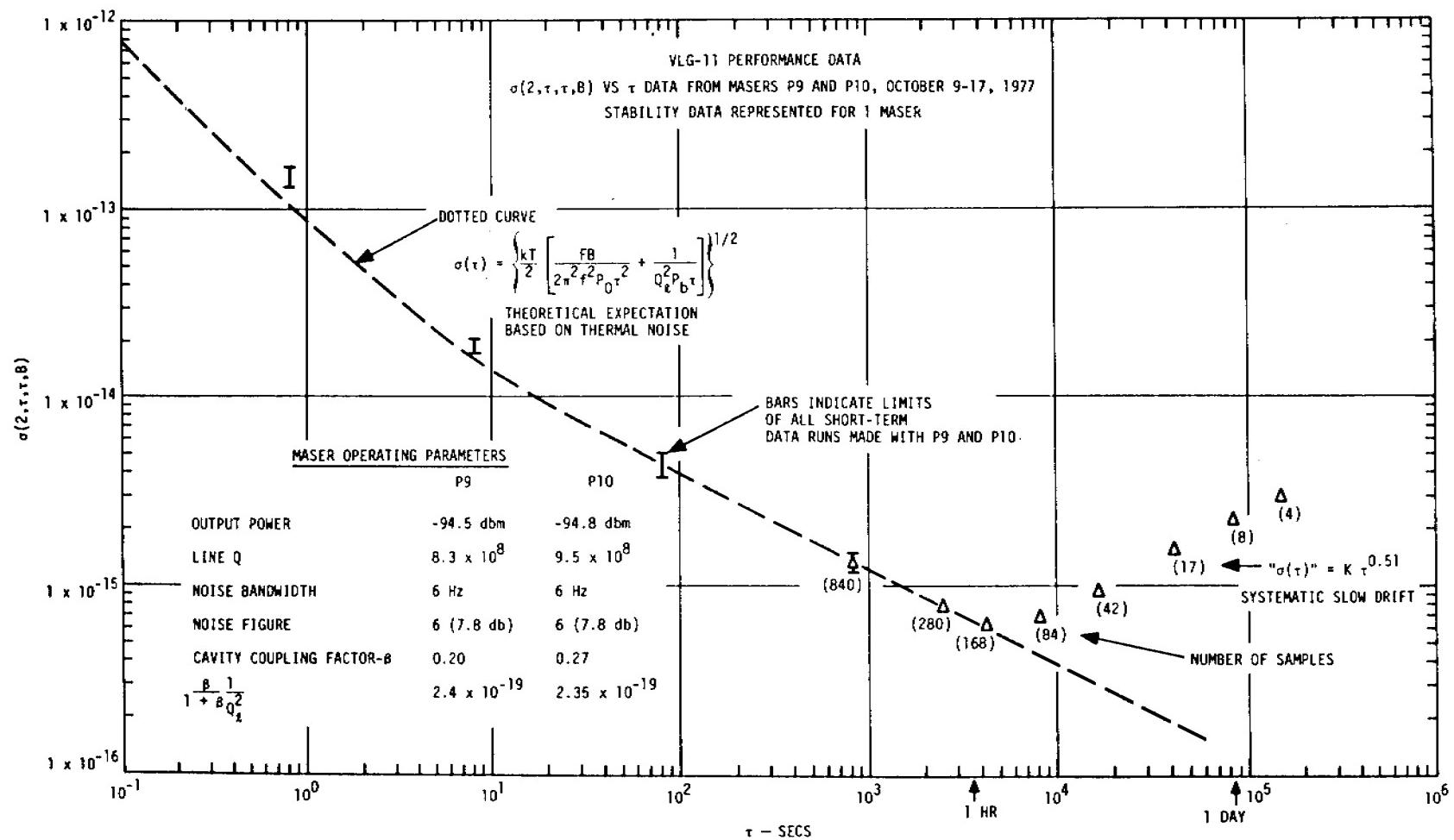


Figure 3. Stability of H-masers showing the effect of systematics.

SCHEMATIC DIAGRAM OF STATE SELECTION SCHEME  
TO OBTAIN HYDROGEN ATOMS ONLY IN THE  
 $F=1, M_F=0$  HYPERFINE STATE

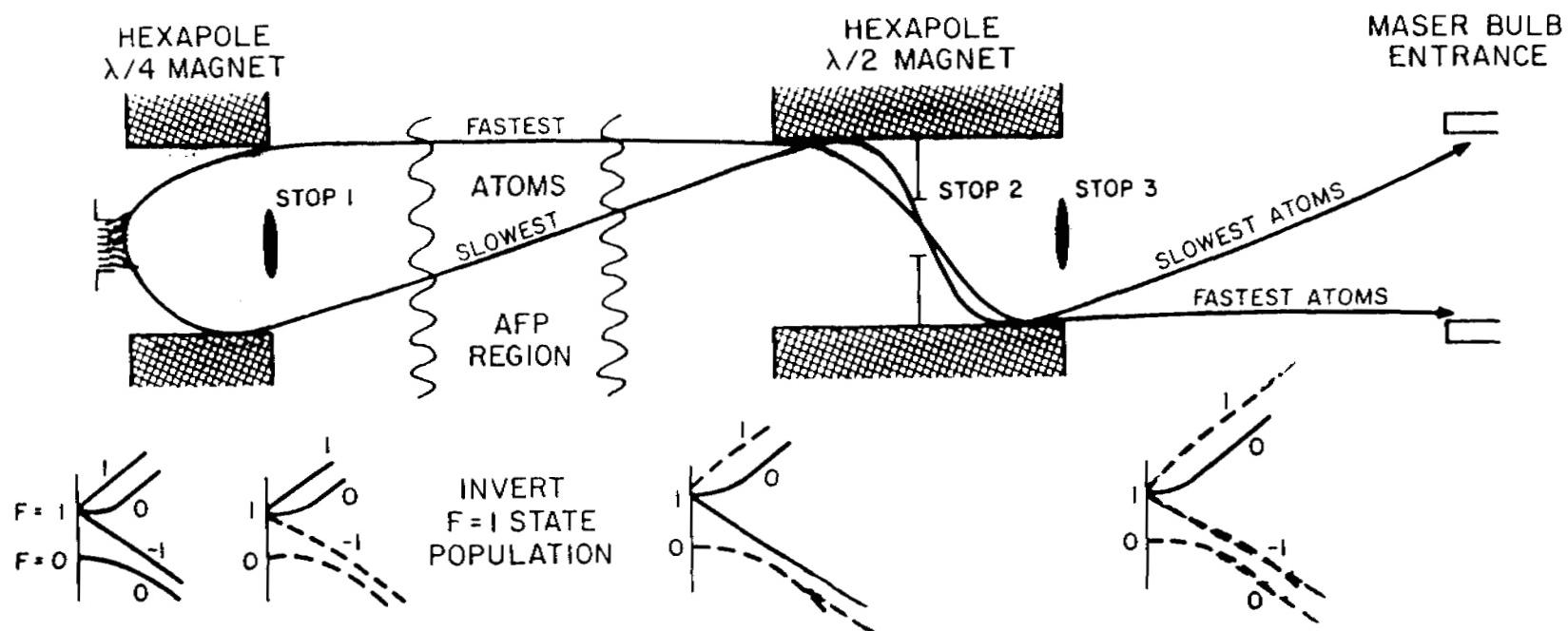


Figure 4.

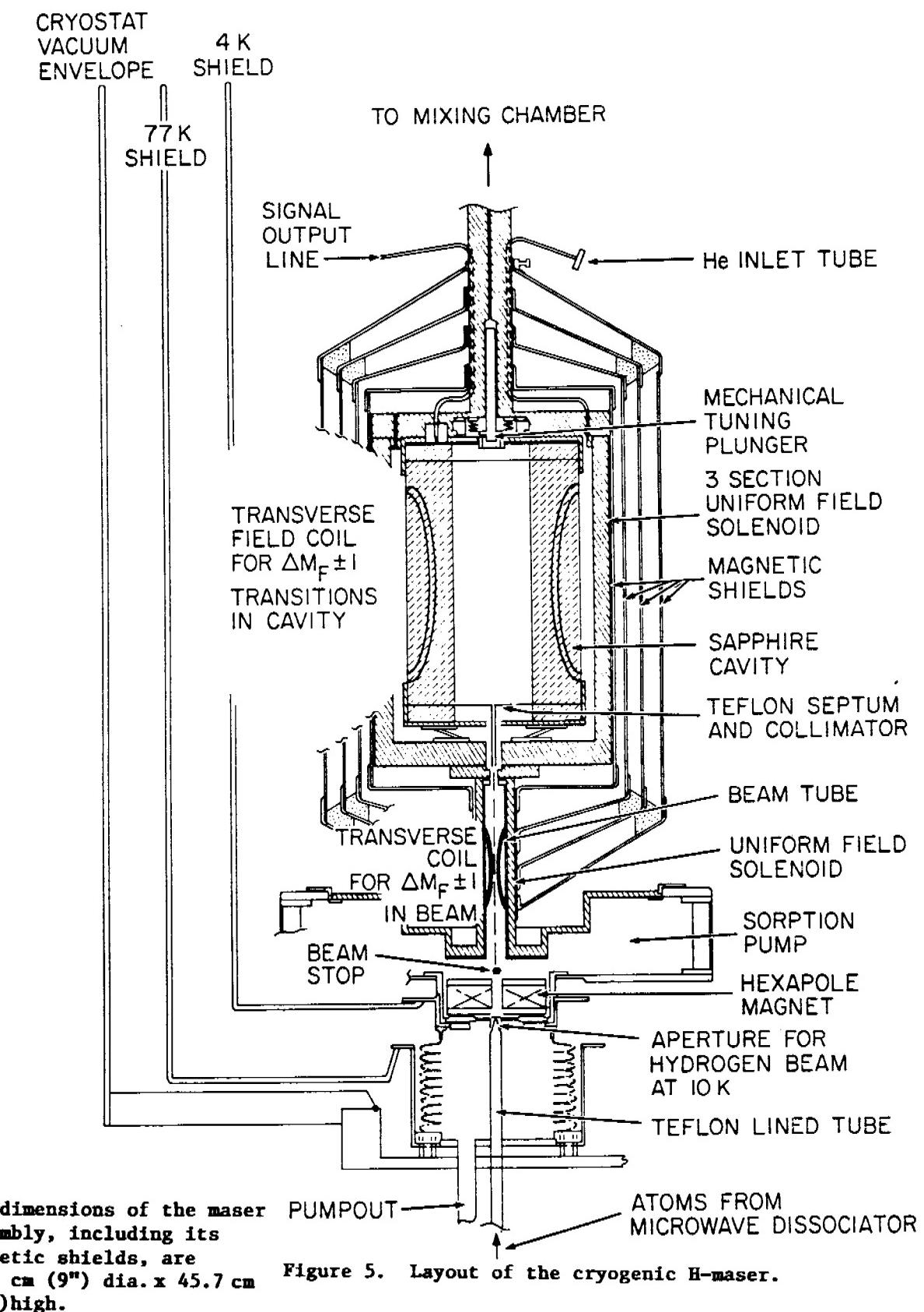


Figure 5. Layout of the cryogenic H-maser.

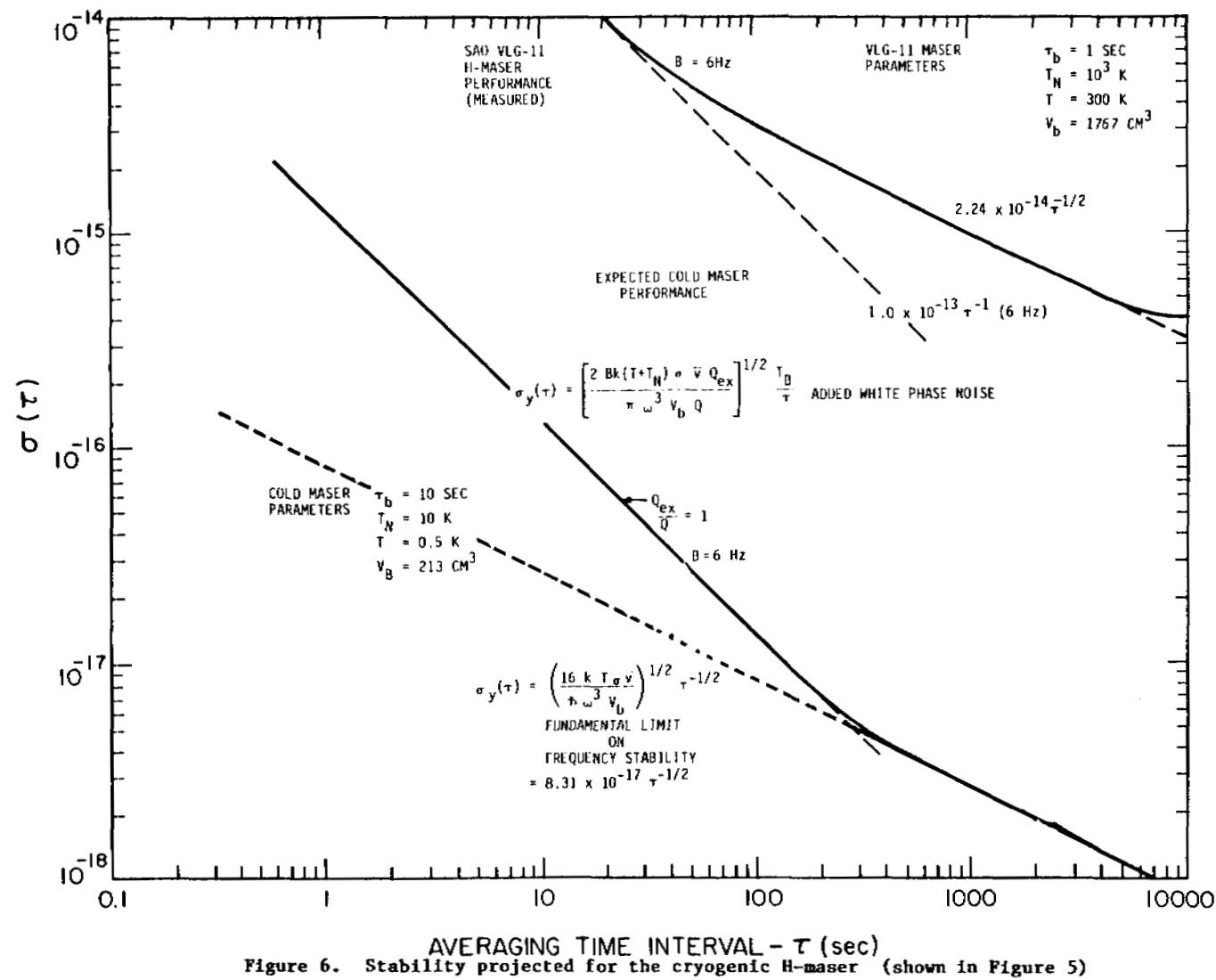


Figure 6. Stability projected for the cryogenic H-maser (shown in Figure 5)

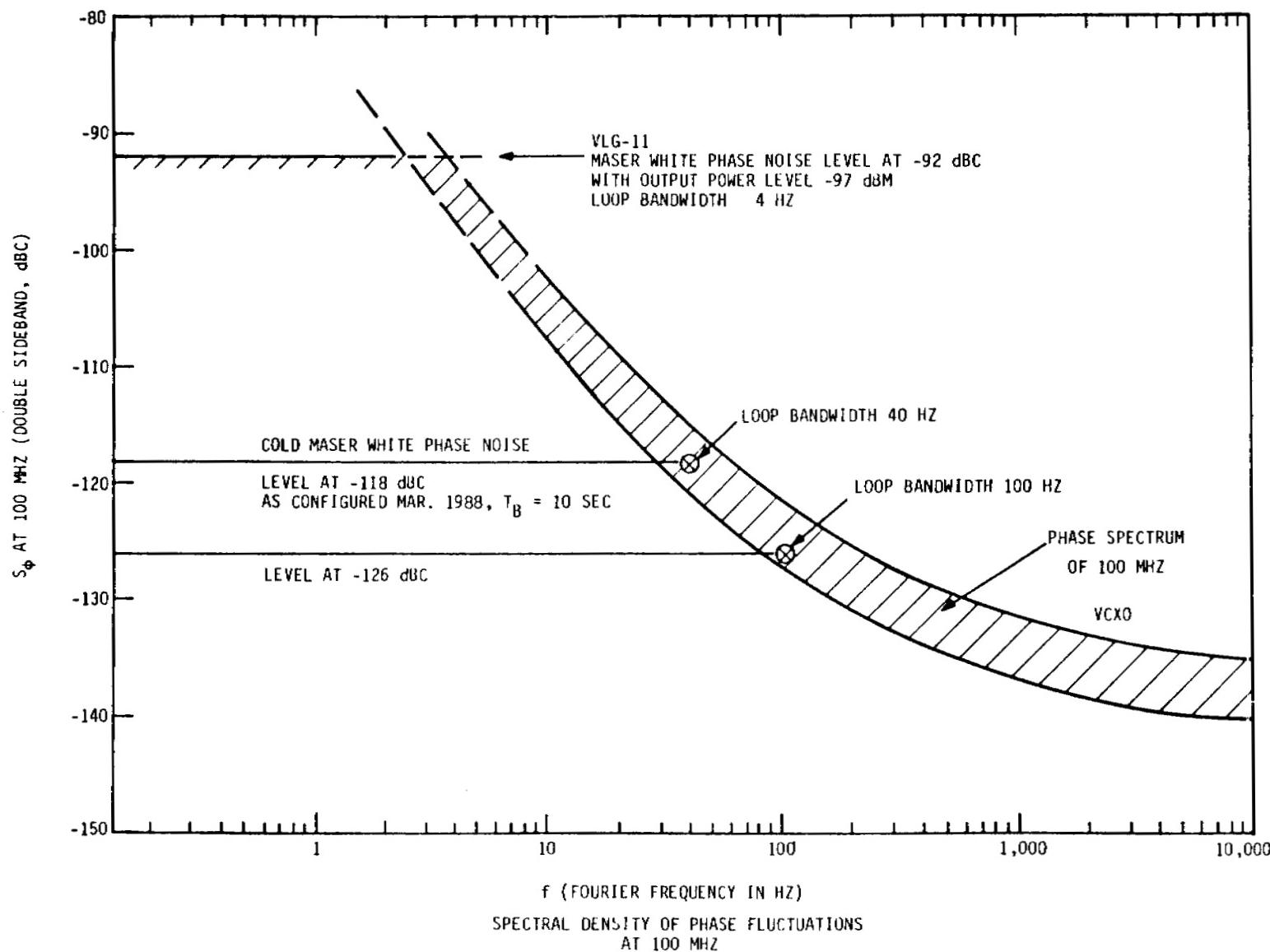


Figure 7. Spectral density of phase fluctuations at 100 MHz for the cryomaser and conventional H-masers.